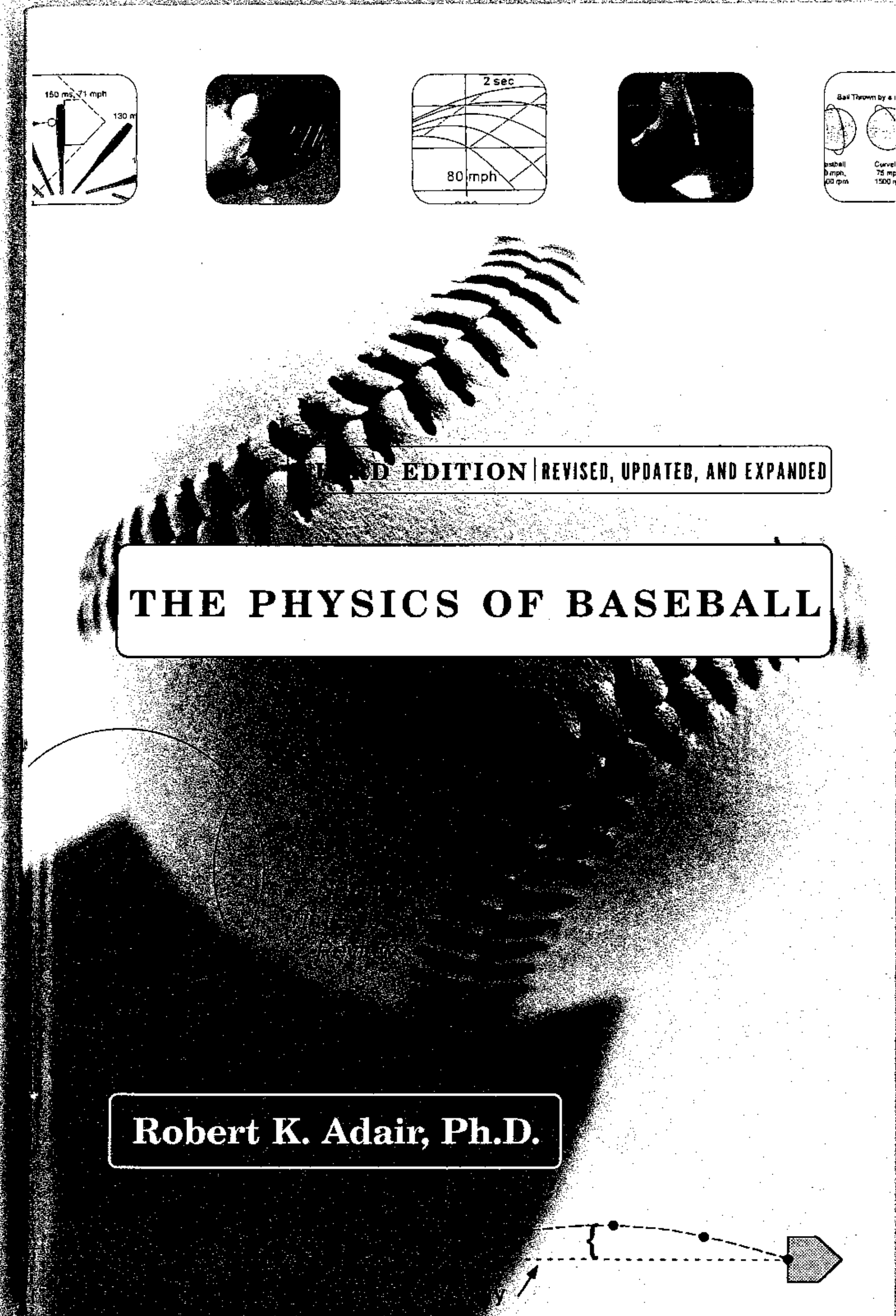
10


2 sec
80 mph
EDITION | REVISED, UPDATED, AND EXPANDED
THE PHYSICS OF BASEBALL
Robert K. Adair, Ph.D.

THE PHYSICS OF BASEBALL

Third Edition, Revised, Updated, and Expanded

ROBERT KEMP ADAIR

Perennial
An Imprint of HarperCollins*Publishers*

hickory bats will retain less of the collision energy for balls hit away from the sweet spot. Also important, the hickory bats and the thick-handled ash bats broke less often.

Although the increase in bat mass of a thicker-handled bat will slow the swing down somewhat, that effect is probably small. Hence, if a player is comfortable using a thicker-handled bat, he might gain a couple of hits on inside pitches over the course of a season. Now they won't break his bat, and he may add a few points to his batting average.

Indeed, in general, bats with thicker handles and bats with longer barrels have longer vibration-free zones of good hitting and are broken less easily by inside pitches. Edd Roush, hitting choked up with his 48-ounce, thick-handled hickory bat in the 1920s, probably never in his life stung his hands hitting an inside pitch and seldom, if ever, broke a bat. The long-barreled "bottle bats" used by players such as Heinie Groh* and Bucky Dent make sense—for some players.

ABERRANT BATS: ALUMINUM BATS

Hollow metal tubing bats—usually from aluminum alloys†—are now used in baseball played outside of the professional leagues. Bats constructed in strange and ingenious ways are used in base-

*Groh's bats had a barrel about 17 inches long, which then necked down abruptly to a rather thin handle that was also about 17 inches long; this odd bat was about half barrel and half handle. Groh swung the 46-ounce bat choked up with his hands spread slightly apart. He had small hands and preferred a thinner handle than was common in the 1920s. Dent used a more conventional bat, but with a long, full barrel that he swung choked up. Groh and Dent were largely line-drive hitters—though both hit important home runs. Indeed, Groh led the 1919 Cincinnati Reds—who beat the Chicago Black Sox in the World Series—in home runs (with 5) and in slugging average (at .431). Recently, some have used the term "bottle bat" differently—for any long-barreled, thin-handled bat.

†The metal bats that sustain the greatest distortion upon impact drive the ball farthest as the recovery of the distortion pushes the ball off of the bat. If the bat does not recover, it's dented and useless—and the ball receives no push and doesn't go anywhere. Considerable ingenuity is applied to finding materials and structures that are maximally flexible but still recover after large distortions—thus the use of special aluminum alloys and titanium. I will use the label "aluminum" for all metal bats.

ball variants, such as various forms of recreational softball, where there seem to be no special constraints on bats. The use of illegally altered bats has occasionally been detected in major league baseball. Questions arise concerning the efficacy of these aberrant bats.

The thin-handled bats made of light wood popular today are fragile, and not cheap. Hence, the cost of bats for amateur baseball is significant, given the economic scale of the sport on that level. Since bats made from aluminum tubing do not break, and can be made with appropriate balance and weight, these bats have become the bats of choice for such baseball and are now allowed by amateur rules. Today, it is hard to find a wooden bat among the rows of aluminum bats in most sporting goods stores.

The requirement that wooden bats be turned from one piece of solid wood places constraints on the size of light bats. Since woods less dense than ash are not strong enough to serve as material for bats, a light bat must perforce contain less wood and be smaller than a heavier bat. Moreover, the weight distribution along the bat is defined by the shape of the bat, and the traditional shape is that which makes the best use of wood.

Since the thickness of the aluminum tubing used to make the hollow aluminum bats can vary over wide limits, the weight and weight distributions of aluminum bats can be set almost independent of the size and shape of the bat. Currently, aluminum bats are shaped like the traditional wooden bats and are made to have similar weights and weight distributions,[f] but this follows from convention rather than mechanical necessity. The freedom of design afforded by aluminum has, however, resulted in the manufacture of light bats with the full-size 2.75-inch barrels allowed by the rules of baseball, while wooden bats must have smaller barrels to keep to the same weight. Hence, the typical 32-ounce wooden bat will have a barrel diameter of only 2.50 inches. With the larger barrel, the 32-ounce aluminum bat will have about a 4 percent larger effective bat-ball hitting surface, with no counteracting disadvantage.

Aluminum bats may also be better than wooden bats in other

ways. The question has been raised as to whether a ball hit by an aluminum bat will go faster and farther than a ball hit by a wooden bat. Players also hold the view that an aluminum bat has a longer region of good hitting than a wooden bat. In particular, balls hit short on the bat—near the handle—are propelled more efficiently by an aluminum bat, and with less vibration and stinging of the hands, than by a wooden bat. And aluminum bats do not break. There appears to be some consensus among players that these reputed advantages of the aluminum bat are real. Are these conclusion correct? And if so, why?

I'll address first the question of the length balls are hit by an aluminum bat (or the speed with which ground balls hit by an aluminum bat travel through the infield). I have noted that the baseball is not very elastic. Even at the moderate velocities used in testing balls, upon striking a hard surface only about 30 percent of the collision energy is returned in the rebound. The return is less than 25 percent for a solid hit off a fastball. A baseball is more elastic than a beanbag, but not by much. The coefficient of restitution for a beanbag striking a hard surface is near zero; beanbags do not bounce at all. No matter how strong a batter is, he cannot hit a beanbag much past second base. Nevertheless, it is possible to design an implement that will hit a beanbag a long way. An examination of such implements can provide some insight into the mechanisms that allow baseballs to be hit farther by bats.

Though we will not be able to hit the beanbag very far with a baseball bat, we will do better with a tennis racket faced with a sheet of very thin rubber rather than with gut or nylon strings. With this contraption, in the collision of the beanbag with the racket, the beanbag will travel past the plane of the racket by perhaps a foot, stretching the rubber. Then the rubber will react, propelling the beanbag away from the racket with a rather high velocity in a kind of catapult effect. Actually, a sheet of rubber would induce too much air resistance for a really fast swing of the racket-bat, and we would do better by stringing the racket with very strong but quite elastic strings.

If we attach a long handle to the tennis racket and weight the racket head to copy the length and weight distribution of a baseball bat, and then swing the racket like a bat, we will be able to hit a beanbag the size and weight of a baseball quite a long way. In fact, could we find strings (perhaps made of steel springs) as elastic as gut or nylon and so strong that they would not snap under the large forces we would generate, we could hit this beanbag farther than a baseball struck by a bat! And indeed, we could hit a baseball farther with our racket-bat than with a regular wooden bat.

I explain this phenomenon by describing the (imaginary) observation of the results of a collision between a specific (also imaginary) racket-bat and the beanbag-ball (a baseball cover stuffed with beans so as to have the same weight as an official ball). The beanbag is flung toward the plate by a major league fastball pitcher and the racket-bat is swung by a major league power hitter. When the beanbag hits the racket face, the strings give way elastically and the bag moves 6 inches past the plane of the racket face. (This deflection is about ten times the compression of the baseball hit by a bat.) Then the strings react elastically, flinging the beanbag back toward the center-field bleachers.

The racket-bat-beanbag collision took place over a time of about $\frac{1}{100}$ of a second (rather than the time of $\frac{1}{1000}$ of a second in the collision of the wooden bat with the baseball) and the maximum force is 800 pounds (rather than the 8000-pound force which reversed the baseball flight). The 800-pound force compressed the soft beanbag-ball 1 inch—and distorted the racket-bat by 6 inches, as previously noted. Then about six-sevenths of the collision energy was stored by the racket and only about one-seventh by the beanbag. Since the beanbag is completely inelastic, all of the beanbag compression energy was lost to friction, but only 40 percent of the energy stored by the racket was lost. For the collision of beanbag and racket, more than 50 percent of the collision energy was returned to the beanbag as kinetic energy in the catapult-like action of the racket on the beanbag; the coefficient of restitution was greater than 0.700.

For a baseball, the energy return is only about 20 percent (corresponding to a COR of about 0.45 at this impact velocity.) A swing that would drive a baseball 400 feet using a wooden bat would drive the beanbag about 480 feet (and a baseball a few feet farther)—the racket-bat would hit a beanbag farther than the wooden bat would hit a baseball! And if the racket-bat were used on a baseball in Yankee Stadium, the ball could well be knocked clear out of the stadium—and not even Babe Ruth ever hit a ball out of that park.

Even an umpire as obtuse as fans claim in their calumny, would be suspicious of such a bat. But aluminum bats do have a little of the catapult-like elastic properties of the racket-bat, and surely *can* hit a baseball appreciably farther than can a wooden bat.

From measurements made by my colleague R. C. Larsen on the compressibility of aluminum bats, it seems that, for a given force, the distortion of an aluminum bat is about one-tenth[g] as great as the distortion of the ball (rather than one-fiftieth, as it is for wooden bats). Moreover, from the high frequency and the persistence of the sound emitted by the bat when stuck lightly at a node of the longitudinal vibration, it appeared that the distortion was quite elastic and that the compression energy would be restored quickly (unlike the longitudinal vibration.) Hence, in this mode, the bat was surely much more elastic than the ball, while the comparatively incompressible wooden bat stored little energy and was only slightly more elastic than the ball. The aluminum bat stored about one-eleventh of the collision energy in a highly elastic deformation of the bat that was returned efficiently to the flight of the ball, while the ball stored about ten-elevenths of the energy in the deformation of the ball, most of which was lost in friction.

Though the intrinsic elasticity of the aluminum bat will be near 100 percent, some of the bat-deformation energy will be retained in the energy of motion of the aluminum shell that makes up the bat. I estimate that 70 percent of the energy stored in the deflection of the aluminum may be returned to the ball. The elasticity of the ball at this impact velocity will be about 20

percent (the square of the coefficient of restitution at the relevant impact force). Using these values, 25 percent of the collision energy will be restored to the aluminum bat and ball, a value much greater than the 20 percent in the collision of the wooden bat and ball. This corresponds to an effective COR of 0.5 rather than the wooden-bat value of 0.45, and the home run hit 380 feet with the wooden bat will go more than 410 feet off the aluminum bat. The same kind of calculations suggest that a fungo hit 330 feet by a (regular) wooden bat would travel about 10 feet farther hit with the same swing by a similar aluminum bat.

Though the numerical values presented here can be considered only as a kind of illustrative estimate—in view of our uncertain understanding of the character of the aluminum bat—the aluminum bats now used for amateur baseball will surely hit a ball appreciably farther than will a wooden bat.

The second purported advantage of the aluminum bat is that it does much better than wood on inside pitches hit too near the handle. The aluminum bat is a kind of shaped hollow cylinder; since aluminum is about four times as dense as ash, to achieve the same weight the bat must be hollow. Aside from the greater strength of the aluminum, along the axis the hollow cylinder is more rigid than is a solid structure containing the same mass of material. The typical aluminum bat is about twice as stiff as a wooden bat of similar dimensions—about twice as much force is required to bend it a given amount. Hence, when a ball is struck badly—near an antinode at the handle or the end of the bat—the stiffer aluminum bat takes up less energy in longitudinal vibration than the wooden bat, and stings the hands less. Moreover, since the vibrational frequency is higher than for a wooden bat, the aluminum bat even returns some of that energy to the ball. Thus a ball mishit near the handle or the end of the bat will go farther off an aluminum bat than a wooden one; there is more room for error with an aluminum bat.

Perhaps more important, the aluminum bat does not break when a ball is hit near its handle. The force of resistance to the ball supplied in the course of the bending of the bat is not trun-

cated by the breaking of the bat. With more force propelling the ball back, the ball will come off the aluminum bat faster—perhaps over the infielder's head—than off the broken wooden bat.

ABERRANT BATS: CORKED BATS

On occasion, players have modified their wooden bats by drilling a hole from the end of the bat along the axis and filling it with cork, cork balls, rubber, or other materials. A wooden cap is placed over the hole, then sanded and varnished to hide the modification. Neither the hole nor the addition of the filling are allowed under baseball rules.

It is desirable to determine whether such an illegal modification might create a bat that has properties that cannot be achieved by a legal bat—and hence might threaten the integrity of the game—or if the effect of the modification can only produce a bat with properties no different than might be achieved by a legal bat. It is not possible to conclude categorically that a specific physical change in a bat is good or bad. But it is possible to determine the character of the change and to determine if the change—if illegal—would produce a bat with characteristics outside of the range covered by bats constructed according to baseball rules.

Ordinarily, we describe a bat by its length and weight. With wooden bats all having similar shapes, that's a useful description. Two bats with the same weight and length will feel about the same when we swing them. But this simple description doesn't work so well in considering bats in which weights are added or subtracted illegally. Obviously, a couple of ounces added or subtracted at the end of the bat changes its character much more than taking away or adding the same weight in the handle would.

The properties of a bat relevant to swinging the bat so that it strikes the ball squarely are largely defined by the *moment of inertia* of the bat about the end of the bat and the pendulum length about the end. That moment of inertia is proportional to the resistance you feel when wagging the bat back and forth with

your hands while keeping your hands in the same place. The pendulum length is the length of a simple pendulum of a bob weight on the end of a string that would oscillate with the same period as the bat suspended at the end. I call that length the "swinging length" of the bat, and define a "swinging weight" as the weight at that point that would give the same moment of inertia as the bat. Thus, if you had a long, almost weightless rod the length of the swinging length, mounted in a bat handle with a weight on the end of the rod equal to the swinging weight, this odd assembly would have the feel of a bat. Swinging it with your eyes closed, you would think that you were swinging a real bat with that swinging weight and swinging length.

For a typical bat 34 inches long weighing 32 ounces, I found a swinging length of 26 inches and a swinging weight of 28½ ounces. An interesting illegal bat modification is made by drilling an axial hole in the end of a bat and filling it with an extraneous material (e.g., cork, cork balls, rubber, rubber balls). The illegal modification was chosen to be a hole 1³⁄₁₆ inches in diameter drilled 6 inches deep along the axis from the barrel end of the bat. The hole was filled with cork. The density of the wood was 0.638—a typical density for American ash (or white ash)—and the density of the cork was 0.25 times the density of water. In this way, the weight of the bat was reduced by about 1½ ounces, centered about 31 inches from the handle end of the 34-inch bat.

This reduces the bat weight by an ounce and a half and, more important, the swinging weight by about the same amount. The swinging length was reduced by about three quarters of an inch. The bat has been changed significantly. It's lighter, and effectively shorter, and one can swing it more quickly. If a player is having trouble getting around on the fastball, this weight reduction will help him in very much the same way that a choice of a lighter bat might help. As with a lighter bat, the batter will probably not drive the fastball as far by 2 or 3 feet when he hits it well with the drilled-out bat, but he may hit it with good timing more often.

Generally, the player who drills out his bat stuffs the hole with cork or rubber. But this added material serves more as a detri-